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Assessing the benefits and costs of renewable electricity. The Spanish case

Margarita Ortega [a], Pablo del Río [b,*], Eduardo A. Montero [c]

[a] Civil Engineering Department – University of Burgos, EPS Burgos, Avenida Cantabria, s/n 09006 Burgos, Spain
[b] Institute for Public Policies and Goods, National Research Council of Spain (CSIC), C/Albasanz 26-28, 28037 Madrid, Spain
[c] Electromechanical Department – University of Burgos, EPS Burgos, Avenida Cantabria, s/n 09006 Burgos, Spain

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ABSTRACT

The aim of this paper is to provide an assessment of the benefits and costs of the deployment of RES-E, electricity from renewable energy sources (RES-E) in Spain between 2002 and 2011. The benefits refer to reductions of CO_2 emissions and fossil-fuel imports. These are compared to the costs of public support for RES-E deployment granted through the feed-in-tariff system (FIT). Three different methods have been applied for this purpose: the operative margin factor, the build margin factor and a combination of both. The results show that the benefits of RES-E promotion have outweighed the overall costs of RES-E deployment, although significant variation can be observed across technologies. While those benefits have been higher than the costs for on-shore wind and small hydro, this is not the case with the solar technologies. The costs have been significantly higher than the benefits in the case of solar photovoltaics and slightly higher in the case of solar thermoelectric.

Contents

Abbreviations: BM, Build margin factor; CCGT, Combined-cycle gas turbines; CDM, Clean Development Mechanism; CM, Combined margin factor; CNE, Spanish National Energy Commission; EU ETS, European Union Emission Trading System; FIT, Feed-in-tariff system; IPCC, Intergovernmental Panel on Climate Change; LHV, Low Heating Value; MINETUR, Spanish Ministry of Industry, Energy and Tourism; NREAP, National Renewable Energy Action Plan; OM, Operating margin factor; PV, Solar photovoltaic; RES-E, Renewable energy sources; SCC, Social Cost of Carbon; TOE, Tonnes of oil equivalent; UNFCCC, United Nations Framework Convention on Climate Change

* Corresponding author. Tel.: +34 91 602 2560.
E-mail address: pablo.delrio@csic.es (P. del Río).

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1. Introduction

In the last years, many articles in the specialised economic press have stated that renewable electricity and the promotion scheme used in Spain to support them (feed-in tariffs or FITs) are "too costly". The main reasons have been a solar boom-and-bust cycle, which led to a tremendous growth in solar photovoltaic (PV) deployment and a large increase in the associated costs of supporting the diffusion of this technology [1]. This reduced the legitimisation of support for all renewable energy technologies, and was a major factor behind the *"sine die moratorium"* of the support system (FIT) in January 2012, after Royal Decree Law 1/2012 [2]. Plants installed after such date will not receive the FIT, which will only be granted to existing plants.

These claims about the excessive costs of supporting electricity from renewable energy sources (RES-E) focus on one side of the overall picture, without taking into account that, in addition to those costs, RES-E brings considerable socioeconomic and environmental benefits in terms of CO_2 emissions reductions and substitution of fossil-fuel imports. The main issue is, then, whether the costs of supporting RES-E deployment are worth paying, given its social, economic and environmental benefits.

The aim of this paper is two fold:

(a) To quantify in monetary terms some of the environmental and socioeconomic benefits of RES-E deployment in Spain in the 2002–2011 period. The environmental benefits refer to the CO_2 emissions avoided as a result of such deployment, whereas the socioeconomic benefits for the country refer to the reduction of fossil-fuel imports.
(b) To compare those benefits with the costs of public support for RES-E deployment granted through the FIT system.

This is a main topic at a time when support for RES-E has been questioned, leading to the aforementioned *"sine die moratorium"*. RES-E deployment has been publicly promoted in Spain since 1994 after Royal Decree 2366/1994 [3], using a feed-in tariff (FIT) system, with partial reforms in 1998, 2004, 2007, 2008 (only for solar PV) and 2010. The Special Regime (under which RES-E and cogeneration are promoted) is currently regulated by Royal Decree 661/2007 [4], which was approved in 2007. RES-E generators have had two alternatives to sell RES-E. One is to sell the electricity directly to the grid. In this case, generators would receive a regulated tariff. Another option has been to sell the electricity through the market operator. RES-E generators would then receive the daily market price of electricity plus a renewable energy premium. In 2008, the Royal Decree 661/2007 was replaced by Royal Decree 1578/2008 only for solar PV [5], which classified solar PV installations into two groups: ground-mounted and roof installations. Annual capacity targets were set and regulated tariffs were reduced every year according to the evolution of installed capacity. Under this flexible degression scheme, support levels and capacity targets were set in a circular manner. If the capacity in the previous quarter increased too much, then the support levels were reduced in order to trigger a smaller capacity increase.[1]

In addition, Law 15/2012 set a tax on electricity production on all sources of electricity generation, including renewable energy plants (a 7% rate) [7]. Recently, Royal Decree-Law 2/2013 has stated that renewable energy plants can only opt for the regulated tariff option (i.e., not the premium one) [8].

[1] For a detailed overview of the functioning of the Spanish FIT, see Refs. [1,6].

Remuneration levels (under both alternatives) have been different for different renewable energy technologies, i.e., lower for the cheapest and higher for the more expensive ones. The total costs for the four renewable energy technologies considered in this study (small hydro, wind, solar PV and solar thermoelectric) increased slowly in the first half of the period, from 996 M€ in 2002 to 2691 M€ in 2007. They reached 4827 M€ in 2007 and 6369 M€ in 2008, and then increased gradually until 2011 (7439 M€) (see Table 6 for further details). The substantial increase from 2006 to 2007 can be attributed to both solar PV and wind, whereas the trend from 2007 to 2008 can only be attributed to solar PV. In 2008, this large increase in the total policy costs led the government to approve Royal Decree 1578/2008, which put a limit (quota) on the amount of solar PV which could be eligible for support and implemented the aforementioned flexible degression scheme. In 2010, three regulations were enacted (Royal Decrees 1565/2010 and 14/2010 and Royal Decree Law 1614/2010), which limited the number of hours of RES-E generation which would be eligible for support, limited the period over which plants could receive the remuneration (instead of lifetime) and reduced the remuneration levels by applying correction factors (0.65 for wind and between 0.95 and 0.55 for solar).

Finally, as mentioned above, the FIT has been suspended *sine die* for new installations after Royal Decree Law 1/2012, although this regulation is not retroactive, i.e., those plants being registered before January 2012 will continue to receive the FIT support levels established in previous regulations (Royal Decree 1578/2008 for solar PV installations and Royal Decree 661/2007 for the rest).

The four technologies selected for this study, jointly account for 93% of all RES-E installed capacity in Spain in 2011 (excluding large hydro). Wind and solar are also the technologies whose deployment has increased most during the 2000–2011 period. They are also the ones being expected to increase most in the short and medium terms, according to the Spanish National Renewable Energy Action Plan (NREAP) [9] submitted to the European Commission to comply with the Renewable Energy Directive (Directive 28/2009/EC).

Several articles have tried to quantify in monetary terms the benefits associated to the deployment of renewable electricity [10–12]. Some authors claim that environmental and non-environmental externalities should be considered when taking decisions on energy matters [13–16]. In fact, internalising those externalities requires a robust and exhaustive quantification of those external costs [17]. This valuation and internalisation is deemed necessary for making efficient social choices. Several papers have focused on the environmental externalities avoided by renewable energy deployment [18–21]. Owen [22] shows that,

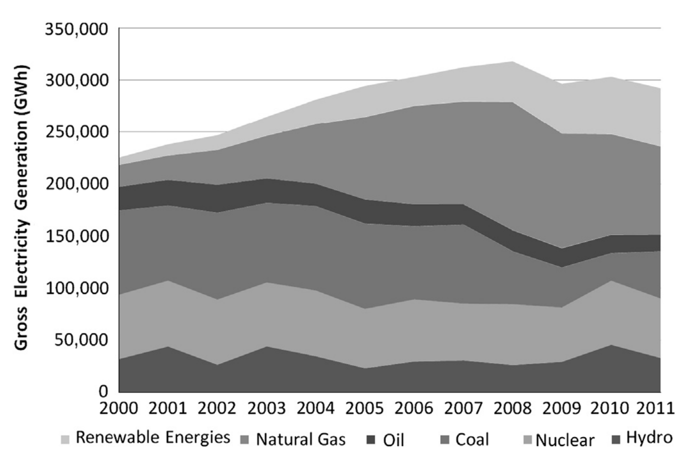

Fig. 1. Evolution of the electricity mix in Spain 2000–2011 [26,27]
Source: MINETUR [26,27].

Table 1
Evolution of RES-E net generation in Spain between 2000 and 2011 (GWh) [26,27].
Source: MINETUR [26,27].

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Small hydro	4229	4572	4056	5190	4605	3699	4027	4006	4515	5131	6608	5126
Wind	4519	6679	9231	11,641	15,500	20,405	22,474	26,688	31,302	36,525	42,561	40,737
Solar PV	21	27	30	38	54	75	162	471	2448	5749	6180	7060
Solar thermoelectric	0	0	0	0	0	0	0	8	15	100	666	1708

if the costs of the damages associated to the burning of fossil-fuels were internalised in electricity prices, several renewable energy technologies (namely wind energy and some biomass technologies) could compete with coal-fired electricity generation. Other authors have focused on the positive non-environmental externalities of RES-E deployment, mostly employment creation [23–25].

Accordingly, the article is structured as follows. The next section provides some data on the trends and penetration levels of renewable electricity in Spain, and gives some details on the support scheme used to promote RES-E. Section 3 discusses the methodology used to assess the benefits and costs of RES-E deployment. The main results are provided in Section 4. Section 5 concludes.

2. Renewable electricity in Spain.

Gross electricity production in Spain amounted to 292,051 GWh in 2011, which represented a reduction of 3.6% with respect to 2010. As shown in Fig. 1, electricity production has had a sustained growth along the period 2002–2009, decreasing slightly in 2010 and 2011 due to the economic crisis and other factors like the improvement of energy efficiency [26,27]. In 2011, Spain had a relatively diversified electricity generation mix, with coal (15%), nuclear (20%), natural gas (29%) and RES (29%) representing significant shares in this mix. Only oil (5.6%) had a negligible share in electricity generation. Within RES, wind (14%) and hydro (10%) dominate, whereas solar (3.2%) and biomass (1.6%) have smaller shares [27].

In the last 12 years, significant changes in its electricity generation mix have taken place in Spain. Ten years ago, in 2002, Spain had an electricity generation mix based on coal (34%), nuclear (25%) and other fossil fuels: natural gas (14%) and oil (11%). RES accounted for 16% of electricity generation. Hydro (11%) was the technology with the highest contribution. The rest had very small shares: wind (4%), biomass and wastes (1.7%) and solar (0%) [28]. As shown in Fig. 1, renewable energy sources significantly increased in the 2000–2011 period, with an average annual growth rate (excluding large hydro) of 22% [26,27]. Among other factors, this can be attributed to a stable and relatively generous RES-E support scheme based on feed-in tariffs (FITs). In 2002 RES-E (excluding large hydro) amounted to 14,033 GWh (5.7%) while in 2011 this amount increased by 56,007 GWh (19.2%).

In 2011, total wind capacity installed in Spain (21,673 MW) was behind the total capacity installed in China, USA and Germany [29,30]. In 2002, the installed wind capacity in Spain was 4366 MW, which involves a growth of almost 400% over the period 2002–2011. With a 4.4 GW accumulated capacity, Spain is still one of the world leaders in solar PV deployment as well, although the growth has been quite low given the capacity caps implemented since 2008 [1]. The growth in this sector was really high in the period 2006–2008 (total PV capacity until 2004 was almost non-existent). Total world accumulated capacity of solar PV amounted to 70 GW in 2011 [31], i.e. Spain represents 6.3% of such world capacity. Regarding solar thermoelectric, the total capacity installed worldwide in 2011 was around 2 GW [32]. Spain is clearly the world leader in this technology, ahead of the United States, with a total capacity installed of 1049 MW in 2010 [33]. Hydro installed capacity was 19.6 GW, of which 2041 MW were from plants with a nameplate capacity lower than 50 MW [33]. According to the Transmission System Operator (REE), in 2002 hydro-capacity was 16.9 GW [34].

Table 1 shows the trends in net electricity generation from those four technologies. Net electricity generation from hydro has increased at an average annual rate of 3.1% in the period 2000–2011. In contrast, the growth rates of solar PV, solar thermoelectric and wind energy have been much greater. Wind energy has increased ten-fold in the period, whereas solar energy generation amounts to 8768 MWh, when it was nil in 2000.

In order to make up for the difference between the high costs of renewable energy generation and the market price of electricity, a FIT was adopted in Spain.[2] This instrument has been implemented in countries with a successful promotion of RES-E deployment, including Germany, Denmark and Spain [35]. The wind energy sector in Spain has been boosted by this scheme and has become a worldwide leader [36–39].

3. Methodology

In order to quantify in monetary terms the CO_2 emissions reductions and the imports of fossil fuel avoided due to the deployment of renewable electricity, and to compare them with the costs of public support through the FIT, we have used a methodology based on the *"Tool to calculate emission factor for an electricity system"* proposed by the United Nations Framework Convention on Climate Change (UNFCCC) [40](see Section 3.1). In this paper, we have adapted this methodology to our task, i.e., we have used it to estimate the technologies which would replace renewable energy technologies for electricity generation in Spain. To our knowledge, this is the first time that this valuable, sound and internationally validated tool has been used for this purpose.

3.1. The UNFCCC methodology

The UNFCCC methodology determines the CO_2 emission factor associated to the displacement of electricity generated by power plants in an electricity system. This tool has mainly been used in Clean Development Mechanism (CDM) projects and it may be applied to calculate baseline emissions for a project activity that substitutes grid electricity, i.e. where a project activity supplies electricity to a grid or a project activity that results in savings of electricity that would have been provided by the grid.

[2] On-shore wind costs in Spain are between 5.9 and 8.9 c€/kWh, depending on the location of the wind farms. The costs of solar PV are within the 14–21 c€/kWh range for ground-mounted installations and in the 24–31 c€/kWh range for roof installations. Solar thermoelectric (parabolic cylinders) costs around 24.8 c€/kWh, whereas the costs of tower systems are 28.4 c€/kWh. Electricity generation from hydro-costs between 7.5 c€/kWh (run-of-river) and 7.3 c€/kWh (dams) [9].

Originally this methodology determines the CO_2 emission factor for the displacement of electricity generated by power plants in an electricity system by calculating the following factors:

(1) *Operating margin factor* (*OM*). The OM is the average CO_2 emissions factor of all power plants serving the grid. It refers to the group of existing power plants whose current electricity generation would be affected by the proposed CO_2 mitigation project (i.e., RES-E project). RES-E generation would replace electricity generated by existing plants which are connected to the distribution grid and whose operation would be affected by RES-E generation. To calculate the *operating margin*, we will use two different methods: the Simple and the Average OM. The simple OM emission factor is calculated as the generation-weighted average CO_2 emissions per unit net electricity generation (tCO_2/MWh) of all generating power plants serving the system, not including low-cost/must-run power plants/units.[3] The simple OM may be calculated using two options [40]. Option *a* is based on the net electricity generation and a CO_2 emission factor of each power unit. Option *b* is based on the total net electricity generation of all power plants serving the system and the fuel types and total fuel consumption of the project electricity system. We use option *b* which, according to the UNFCCC, can only be used if the necessary data for option *a* is not available, which is our case. The average OM emissions factor is elaborated as the simple OM, but it includes the low-cost/must-run technologies in the relevant equations.

(2) *Build margin factor* (*BM*). The BM is the generation-weighted average emission factor (tCO_2/MWh) of all power units *m* during the most recent year *y* for which electricity generation data is available. It refers to the group of prospective power plants whose construction and future operation would be affected by the increase in RES-E generation. RES-E generation would replace electricity generated by plants which have either delayed or cancelled their operation (due to the installation of RES-E plants). In Ref. [40], the UNFCCC states that the sample group of power units *m* used to calculate the BM should be based on the five power units that started to supply power units more recently. Therefore, in order to calculate the *build margin*, we assume that if RES-E deployment had not taken place during this period in Spain, such renewable electricity would have been supplied by CCGT plants. This is so because, apart from RES-E, gas-fired combined cycles (CCGT) have been the only type of plants increasing their installed power during the period considered in this paper (2002–2011) [26,27].

(3) *Combined margin factor* (*CM*). This is a weighted average of both factors.

Given that the BM is more restrictive than the simple OM, we will use both methods. Furthermore, since our analysis takes into account the impacts of RES-E plants on the existing power plants (OM) and the construction of new facilities avoided in the period (BM), we have used the CM, following the recommendation of Kartha et al. [41].

We use the *weighted average CM*, where the OM and the BM have equal weights. We assume two different scenarios (Options A and B). Both use the BM in the same proportion, but one uses the simple OM and the other uses the average OM:

$$\text{Option A}: \ F_{CM1} = 0.5F_{\text{Simple OM}} + 0.5F_{BM} \quad (1)$$

$$\text{Option B}: \ F_{CM2} = 0.5F_{\text{Average OM}} + 0.5F_{BM} \quad (2)$$

where, F_{CM} is the *Combined Margin Factor*, $F_{\text{Simple OM}}$ is the *operating margin factor* using the simple method, the $F_{\text{Average OM}}$ is the *operating margin factor* using the average method and the F_{BM} is the *build margin factor*.

3.2. Methodological adaptation: a tool to calculate the benefits of RES-E deployment

This methodology was not originally conceived for the purposes of this paper. Therefore, we adapt it to our aims, and we develop an innovative yet internationally validated tool. Some studies have used a similar methodology. For instance, the International Energy Agency has used the *build margin* factor, assuming that PV would replace gas-fired electricity generation in the calculation of carbon abatement in Germany [42]. Other studies assume the replacement of RES-E by electricity from coal plants [43] or from a mix of coal and natural gas plants [44]. Moran and Sherrington [45] consider three possible scenarios for the carbon dioxide emissions avoided: substitution by coal, substitution by the electricity generation mix of the corresponding year and substitution by natural gas.

The methodology we employ allows us to calculate the CO_2 emissions avoided due to RES-E generation (different technologies) and to translate these CO_2 emissions avoided into monetary terms. Regarding the calculation of the amount of fossil fuels which is no longer imported due to their replacement by RES-E, and in line with our scenarios, we assume two *Combined margin factors* (Options A and B). We then translate those fossil fuel savings into monetary units by multiplying the physical saving by the price of each fuel.

Once those savings have been calculated and translated into monetary units, they are compared to the costs of public support in the form of feed-in tariffs (FIT), which is the support instrument used in Spain during the analysed period. The relevant support is that which covers the difference between the support level of the FIT and the wholesale price of electricity. Fig. 2 and the rest of this section provide more details on the methodology.

3.2.1. Transform final energy into primary energy

The following identity is used to transform final energy (electricity) into primary energy in all our methods:

$$1\ \text{MWh(Primary Energy)} = 1/\eta\ \text{MWh(Final Energy)} \quad (3)$$

whereas η is the electricity performance rate. The Spanish Ministry of Industry, Energy and Tourism (MINETUR) provides annually the necessary data to calculate the performance rate of each type of plants on an annual basis [46]. The following equation has been used for this purpose:

$$\eta = m \times \text{LHV/Net electricity production} \quad (4)$$

m is the quantity of fossil fuel (ton or m^3) and LHV is the Low Heating Value (Gcal/ton or m^3). 1 Gcal = 1163 MWh.

Table 2 shows the real performance rates of Spanish plants. They are lower than the theoretical shown in the document “Decision of the European Commission 2007/74/EC” [47] and the UNFCCC itself [40]. For reasons of simplicity, we assume that the efficiency of fossil fuel plants does not change when they are substituted by renewable energy plants. In reality, however, a small increase in those efficiencies could be expected.

[3] Low-cost/must-run resources are power plants with low marginal generation costs or that are dispatched independently of the daily or seasonal grid load. Both nuclear and renewable energies (including hydro) have been included in this category.

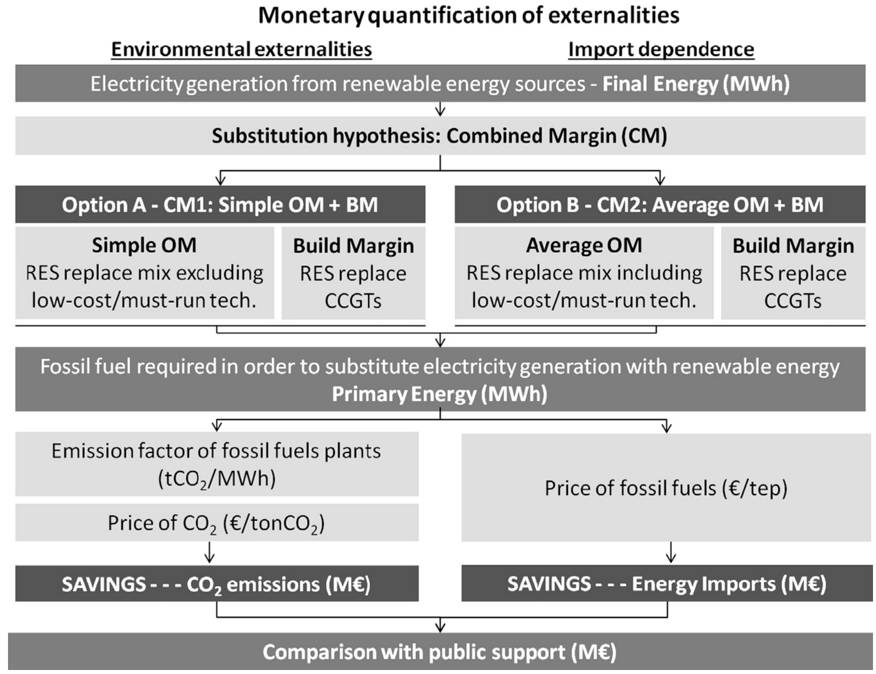

Fig. 2. Illustrating the methodology to calculate the CO_2 savings and energy imports. Abbreviations: CM: Combined Margin Factor; OM: Operating Margin Factor; BM: Build Margin Factor; RES: Renewable Energy Sources; CCGT: Combined Cycles Gas Turbine.

Table 2
Real performance rates in Spanish plants.
Source: MINETUR [46].

Technology	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Coal (%)	36.7	36.9	36.7	36.5	35.4	35.4	35.6	34.8	33.8	33.0
Oil (%)	39.3	39.1	38.5	38.6	38.5	39.3	42.6	42.1	40.0	39.8
Natural Gas (GFCC) (%)	50.0	53.3	53.5	48.9	50.4	51.8	50.9	50.1	49.9	51.6
Nuclear (%)	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0

Table 3
Combined margin factors used (Options A and B): conversion factor (final energy to primary energy), emission factor and prices.
Source: Own elaboration.

Parameter	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Conversion Factor – Final Energy to Primary Energy										
Simple OM	2.525	2.441	2.398	2.423	2.370	2.341	2.226	2.239	2.246	2.339
Average OM	2.470	2.326	2.351	2.397	2.295	2.247	2.170	2.110	2.045	2.143
Build Margin BM	2.002	1.876	1.869	2.045	1.986	1.931	1.966	1.996	2.006	1.937
Combined Margin – Opt. A	**2.263**	**2.159**	**2.134**	**2.234**	**2.178**	**2.136**	**2.096**	**2.117**	**2.126**	**2.138**
Combined Margin – Opt. B	**2.236**	**2.101**	**2.110**	**2.221**	**2.141**	**2.089**	**2.068**	**2.053**	**2.025**	**2.040**
Emission Factor (tCO_2/GWh)										
Simple OM	0.780	0.742	0.714	0.693	0.657	0.654	0.575	0.568	0.558	0.631
Average OM	0.453	0.394	0.405	0.433	0.403	0.406	0.351	0.319	0.258	0.314
Build Margin BM	0.402	0.377	0.375	0.411	0.399	0.388	0.395	0.401	0.403	0.389
Combined Margin – Opt. A	**0.591**	**0.559**	**0.545**	**0.552**	**0.528**	**0.521**	**0.485**	**0.485**	**0.480**	**0.510**
Combined Margin – Opt. B	**0.427**	**0.386**	**0.390**	**0.422**	**0.401**	**0.397**	**0.373**	**0.360**	**0.331**	**0.352**
Prices (€/toe)										
Simple OM	115.2	122.9	150.8	173.0	216.1	218.4	312.2	224.6	250.8	305.2
Average OM	66.9	65.4	85.6	108.2	132.4	135.6	190.6	126.2	116.2	152.1
Build Margin BM	137.8	143.6	138.8	188.9	250.1	234.2	314.5	244.7	241.6	305.0
Combined Margin – Opt. A	**126.5**	**133.3**	**144.8**	**180.9**	**233.1**	**226.3**	**313.3**	**234.6**	**246.2**	**305.1**
Combined Margin – Opt. B	**102.4**	**104.5**	**112.2**	**148.5**	**191.2**	**184.9**	**252.5**	**185.5**	**178.9**	**228.5**

Table 3 shows the conversion factor from final to primary energy, the CO_2 emission factor (tCO_2/GWh) and the price (€/toe) that we obtain when applying the aforementioned methodology.

3.2.2. CO_2 emissions savings

This is calculated using the two methods developed for the *combined margin*. Once we calculate the primary energy needed to

produce 1 MWh of electricity in a fossil fuel plant, we apply the default emission factor recommended by the IPCC, taking into account only the emissions from fossil fuel combustion [48], using the oxidation factor recommended by the Decision of the European Commission 2007/589/EC [49]. The oxidation factors for the three fuels considered are the following: coal – anthracite (99%), fuel oil (99.5%) and natural gas (99.5%). The emissions factors are: coal – anthracite (97.3 tCO_2/TJ); fuel oil (77 tCO_2/TJ) and natural gas (55.8 tCO_2/TJ).

The following identity is used to calculate the OM emission factor:

$$EF_{OM} = (\Sigma EG_m \times EF_{EL,m})/\Sigma EG_m \quad (5)$$

where EF_{OM} is the *operative margin factor* (tCO_2/MWh); EG_m is the net electricity generated by technology *m* (MWh), $EF_{EL,m}$ is the CO_2 emission factor of technology *m* and *m* are the technologies serving the system (Simple OM: all technologies not including low-cost/must-run power plants/units and Average OM: all power generation technologies in the system).

To calculate the *build margin*, we assume that, if RES-E plants had not been installed, all the energy produced by RES would have been produced by CCGT plants. We use the annual performance for this kind of plants (Table 2) and the emission factor for natural gas (see above).

Table 3 shows the CO_2 emission factor for the *combined margin* (Options A and B).

3.2.3. Fossil fuel import savings

The prices of fossil fuels have historically oscillated in a significant manner. They have shown an upward trend for most of the considered period (2002–2011) [26]. In order to calculate the amount of fossil fuels that have been saved due to RES-E generation, we transform final energy (electricity) into primary energy, according to Eq. (3). Then, electricity in terms of MWh has to be converted to electricity in terms of tonnes of oil equivalent (TOE) and, then, it should be multiplied by the corresponding conversion factors according to the following criteria: Coal: 1 toe = 2.44 t; Oil: 1 toe = 7.06 barrels; Natural gas: 1 toe = 40 × 10^6 Btu.

According to data on the price for uranium provided by the International Monetary Fund [50] and the real consumption of uranium in Spain [46], the uranium prices in 2002 were 0.3 €/toe and 2.1 €/toe in 2010. The price of this fuel is negligible compared to the price of other fossil fuels. Therefore, it was not included in the study.

Fig. 3 illustrates the trend of the fossil fuel prices in the last 11 years which, calculated as €/toe, has substantially increased over the period, with a peak in 2008 [51].

Table 3 shows the parameters used in the study for the calculation of the combined margin, distinguishing between Options A and B.

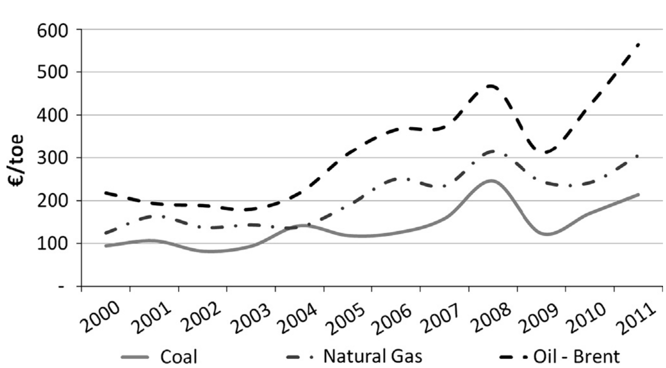

Fig. 3. Evolution of fossil fuel prices .
Source: Own elaboration and BP Statistical Review [51].

4. Results

4.1. Monetary valuation of CO_2 emissions avoided

The methodology developed in the previous section has been applied to calculate the CO_2 emissions avoided by RES-E generation. The CO_2 emissions avoided have increased, according to both methods, more than three-fold in the 2002–2011 period. As a result of the total increase of RES-E deployment in those years, the emissions have been reduced in 2011 by between 28 and 19 million tonnes of CO_2, depending on whether we use scenario A and B for the calculation. In the period 2002–2011 the total amount of emissions have been reduced by 168 and 122 million tonnes of CO_2, respectively, leading to monetary savings of between 1714M€ and 5386M€, depending on the combined option and the scenario chosen. Wind is the renewable energy technology contributing most to the reduction in CO_2 emissions, although solar has increased the most in relative terms. The contribution of solar PV and small hydro is similar in this context, whereas the contribution of solar thermoelectric is currently very small (see Table 7).

We then calculate the emissions avoided in monetary terms. Although there are many studies on the Social Cost of Carbon (SCC) [52–54], we use the SCC reported by Tol [55]. We consider two different scenarios, one with the mode (scenario 1) and the other one with the median (scenario 2). The mode (€14/t CO_2) is similar to the prices of allowances in the European Union Emission Trading System (EU ETS). The median is €32/t CO_2. In monetary terms, RES-E deployment led to CO_2 savings of 390–269M€ in 2011 (110–80M€ in 2002) considering scenario 1, and savings of 892–615M€ (252–182 M€ in 2002) considering scenario 2. Taking into account the EU ETS allowance price, the savings in 2011 have amounted to between 332 and 229M€ (101–73M€ in 2002). Avoided CO_2 emissions and the monetary valuation of CO_2 emissions avoided are shown in Table 4.

4.2. Energy imports avoided

RES-E deployment would lead to a lower consumption of fossil fuel and, thus, lower fossil fuel imports. We estimate that those lower imports were between 10.05 (option A) and 9.58 (option B) Mtoe in 2011. Translated into monetary terms, those savings represent between 3065 and 2190M€ in 2011. Again, wind was the greatest contributor, with a 75% share. Table 5 shows the energy imports avoided in Mtoe during the period 2002–2011 and Table 7 shows the associated economic benefits.

4.3. The costs of public support

As mentioned in Section 3, the Spanish support scheme for RES-E deployment is based on FITs. Net FIT support is measured as the “equivalent FIT” (last column in Table 6), which, according to the National Energy Commission (CNE), represents the total amount of public support.[4] Note that, in 2011, the greatest amount of unitary support (€/MWh) was granted to solar PV, followed by solar thermoelectric. Solar PV also represented the largest share in the total amount of support received. Total support increased significantly between 2007 and 2009, mostly due to the solar boom, with installed capacity of solar PV increasing ten-fold between 2007 and 2008, from 350 MW to 3500 MW.

[4] The so-called “equivalent premium” is calculated as the gross amount of total support minus the wholesale market price of electricity multiplied by the amount of RES-E generation, Circular 4/2009 (CNE) [56].

Table 4
Avoided CO_2 emissions in the period 2002–2011 due to the deployment of RES-E in Spain.
Source: Own elaboration.

Parameter	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	TOTAL
Avoided CO_2 emissions (MCO_2/year)											
Combined Margin – Option A	7.9	9.4	11.0	13.3	14.1	16.2	18.6	23.0	26.9	27.9	**168.3**
Combined Margin – Option B	5.7	6.5	7.9	10.2	10.7	12.4	14.3	17.1	18.5	19.2	**122.5**
Monetary valuation of environmental benefits (Million Euros) – Scenario 1 – SCC=14 €/tCO_2 (Mode) [55]											
Combined Margin – Option A	110.2	132.1	153.7	186.8	197.2	227.4	259.9	322.2	376.7	390.1	**2356.3**
Combined Margin – Option B	79.7	91.1	110.2	142.9	149.6	173.3	199.9	239.5	259.3	269.0	**1714.4**
Monetary valuation of environmental benefits (Million Euros) – Scenario 2 – SCC=32 €/tCO_2 (Mode) [55]											
Combined Margin – Option A	251.8	302.0	351.4	427.1	450.6	519.8	594.0	736.6	861.0	891.6	**5385.9**
Combined Margin – Option B	182.1	208.2	251.8	326.6	342.0	396.0	456.9	547.4	592.7	614.8	**3918.5**

Abbreviations: SCC: Social Cost of Carbon.

Table 5
Energy imports avoided due to the deployment of RES-E in Spain.
Source: Own elaboration.

	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	TOTAL
Energy imports avoided (Mtoe/year) – Combined Margin – Option A											
Small hydro	789	964	845	711	754	736	814	934	1208	943	**10,401**
Wind	1797	2161	2844	3920	4210	4903	5642	6651	7781	7490	**49,570**
Solar PV	6	7	10	14	30	87	441	1047	1130	1298	**4079**
Solar thermoelectric	0	0	0	0	0	1	3	18	122	314	**458**
Energy imports avoided (Mtoe/year) – Combined Margin – Option A											
Small hydro	780	938	836	707	741	720	803	906	1151	899	**10,132**
Wind	1775	2103	2813	3898	4137	4795	5568	6448	7413	7147	**48,199**
Solar PV	6	7	10	14	30	85	435	1015	1076	1239	**3925**
Solar thermoelectric	0	0	0	0	0	1	3	18	116	300	**437**

4.4. Comparing benefits and costs

The results in Table 7 show that, in the 2002–2011 period, the overall accumulated costs of RES-E support (i.e., aggregation of the four technologies considered in this paper) amounted to 22,038 M€. Since the benefits were in a range of 16,715–19,745M€ (Option A: scenario 1 and 2) and 12,575 *y* 14,780 (Option B: scenario 1 and 2 respectively), the support costs substantially outweighed the benefits in Option A by 5323 and 2293M€, and in Option B by 9462 and 7258, considering scenario 1 and 2, respectively. This is mostly due to the imbalance in the realm of solar PV, with costs outweighing benefits by 7496 and 7993M€ in the considered period. In fact, a closer look at the different technologies reveals that the benefits are above the support costs in the cases of wind on-shore for both options A and B. They are slightly above for small hydro and the benefits are only slightly below the support costs for solar thermoelectric. This later technology started production in 2008 in Spain. In option A, while costs were higher than the benefits in the first years of the period for wind on-shore and small hydro, the benefits increased at a faster pace than the costs and the former exceeded the later after 2004 for both scenarios. Since option B is more conservative, the benefits were generally lower than the cost during the period in scenario 1 and slightly higher in scenario 2, with some exceptions.

4.5. Policy implications

Our results show that public support for renewable energy sources generally bring considerable socioeconomic and environmental benefits which outweigh the costs of public support for the most mature technologies (wind on-shore and small hydro). This implies that the *sine-die moratorium* established in January 2012 cannot be defended on the grounds of a cost-benefit analysis, since it takes a one-sided view of the costs of RES-E while neglecting the benefits. Furthermore, this moratorium does not differentiate between renewable energy technologies when our results show that the level of costs and benefits clearly differ across technologies. While policy costs outweigh the benefits in the case of the solar technologies, two remarks are worth making in this regard. First, this can be considered a normal situation given the higher costs of these technologies. The issue is not only whether their costs are higher than the benefits now, but whether they will be so in the future. If we analyse the cases of wind and small hydro over the ten-year period, we note that the costs are initially higher than the benefits, but that the later tend to offset the former over time. Furthermore, recall that some benefits have been left out of the picture (industry creation, jobs and innovation).

On the other hand, the costs of public support for solar PV could have been lower if the policy had been designed in an appropriate manner, i.e., the fact that those costs are higher than the benefits might be unavoidable, but not the extent of such difference. In particular, a relatively generous remuneration was coupled with an absence of a limit on the amount of solar PV generation which was eligible for support. This, together with other factors (see [1]) led to the large increase in policy support costs mentioned in Section 1.

Therefore, the reasons for the moratorium have to be found elsewhere. They are related to concerns about the so-called *tariff deficit* and some specific features of the Spanish electricity system. The *tariff deficit* refers to the fact that electricity prices have been below electricity generation costs, because since 2002 an upper limit on the increase in electricity tariffs for consumers was set. This has created a huge accumulated deficit of around 27,000M€ in 2012 (around 3% of Spanish GDP), which represent a debt of electricity consumers with the electric utilities. One, albeit certainly not the only, reason for the increase in the tariff deficit have been the FIT for RES-E. On the other hand, there is over capacity in

Table 6
Public support received by the renewable energy technologies in the 2002–2011.
Source: CNE [57].

Year	Technology	Total amount supported (thousand €)	Total Average total support (cent€/kWh)	Average wholesale market price (cent€/kWh)	Equivalent FIT (thousand €)
2002	Solar	1358	28.63		1.195
	Wind	708,739	7.38		378.911
	Small hydro	285,942	7.33		151.951
Total 2002		996,039	14.45	*3.43*	532.057
2003	Solar	2889	30.80		2889
	Wind	753,185	6.24		753.185
	Small hydro	335,555	6.59		335.555
Total 2003		1,091,629	14.55	*3.81*	1091.629
2004	Solar	6791	36.74		61.46
	Wind	1,013,031	6.30		451.667
	Small hydro	316,587	6.66		150.753
Total 2004		1,336,409	16.57	*3.49*	608.566
2005	Solar	16,410	39.91		13.996
	Wind	1,856,465	8.76		612.785
	Small hydro	336,154	8.80		111.955
Total 2005		2,209,029	19.16	*5.87*	738.736
2006	Solar	45,589	42.75		39.891
	Wind	2,103,682	9.08		865.815
	Small hydro	371,181	8.95		149.567
Total 2006		2,520,453	20.26	*5.34*	1,055.273
2007	Solar	215,579	43.39		194.819
	Wind	2,157,034	7.81		1,003.575
	Small hydro	319,376	7.74		146.946
Total 2007		2,691,989	19.65	*4.18*	1,345.340
2008	Solar	1,155,068	45.32		990.830
	Wind	3,226,384	10.04		1,155.818
	Small hydro	446,051	9.61		147.033
Total 2008		4,827,503	21.66	*6.44*	2,293.680
2009	Solar	2,868,326	46.24		2,634.250
	Wind	3,061,774	8.01		1,619.203
	Small hydro	439,487	8.07		234.061
Total 2009		6,369,587	20.77	*3.77*	4,487.515
2010	Solar PV	2,899,462	45.28		2,652.892
	Solar thermoelectric	211,503	30.58		184.872
	Wind	3,364,580	7.80		1,964.246
	Small hydro	528,007	7.83		296.940
Total 2010		7,003,553	22.87	*3.65*	5,098.949
2011	Solar PV	2,785,336	37.61		2,400.564
	Solar thermoelectric	519,343	29.19		426.909
	Wind	3,676,959	8.79		1,710.010
	Small hydro	457,857	8.68		206.407
Total 2011		7,439,495	21.07	*4.94*	4,743.890

the Spanish electricity as a result of large investments in combined cycle gas turbines and RES-E, in a context of severe reductions in electricity demand due to the economic crisis. The excess supply cannot be sold abroad, given the limited degree of international interconnections of the Spanish system. Spain is virtually an energy island. Thus, the government decided that no more renewable electricity generation capacity should be added to the system.

5. Conclusions

This paper has compared the benefits and costs of RES-E deployment in Spain in the 2002–2011 period, using an innovative yet internationally validated methodology, which has not been used in the past for the purposes of this paper. The benefits refer to reductions of CO_2 emissions and energy imports, while the costs refer to the amount of public support being granted to RES-E generators. We consider four different scenarios of the developed methodology and the results show that those benefits have been significantly higher than the costs in the considered period for on-shore wind and slightly higher for small hydro. In contrast, the costs are significantly higher than the benefits in the case of solar PV and slightly higher for solar thermoelectric. Therefore, the adage that “RES-E support is too costly” does not stand empirical scrutiny when the benefits from those policy support costs are taken into account. This is certainly the case with solar technologies but not with wind on-shore or small hydro.

The fact that the relatively high costs for the consumers are above the relatively limited external costs avoided by the solar technologies does not mean that they should not be promoted in the future. But the justification for their promotion must probably lie elsewhere, not in those benefits, at least at the beginning of their diffusion curve. While dynamic efficiency (innovation) benefits could provide such a rationale, this is also problematic, since the capacity of a given country to grasp all the benefits from supporting a technology (in terms of technology cost reductions due to advancements along the learning curve) is very limited, in so far as those benefits spill over to actors in other countries. The Spanish experience also shows that the local benefits of industry creation have been modest in the solar PV realm, since most of the solar PV modules installed in the 2007–2012 period were imported [1].

While this paper has compared some of the benefits and costs of RES-E promotion, other benefits and costs have not been considered, given the lack of appropriate data. First, when calculating the CO_2 emissions avoided by RES-E deployment, we have

Table 7
Comparison between benefits and support costs of renewable energy deployment in Spain 2002–2011 (M€)
Source: Own elaboration.

	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	Total
Combined margin – Option A											
Wind energy											
Energy import savings (1)	227	288	412	709	981	1110	1768	1561	1915	2285	*11,256*
CO_2 emissions avoided – Sce. 1 (2)	76	91	118	158	166	195	213	248	286	291	*1842*
CO_2 emissions avoided – Sce. 2 (2)	175	208	270	360	380	445	486	566	654	665	*4209*
Total benefits – Sce.1 (3)=(1)+(2)	304	379	530	867	1147	1304	1980	1808	2202	2576	*13,098*
Total benefits – Sce.2 (3)=(1)+(2)	402	496	682	1070	1361	1555	2254	2127	2570	2950	*15,466*
Public support (4)	379	753	452	613	866	1004	1156	1619	1964	1710	*10,515*
Net benefits – Sce.1 (5)=(3)-(4)	−75	−374	78	254	282	301	825	189	237	866	*2583*
Net benefits – Sce.2 (5)=(3)-(4)	23	−257	230	457	495	551	1098	508	605	1240	*4951*
Small hydro											
Energy import savings (1)	100	128	122	129	176	167	255	219	297	288	*1881*
CO_2 emissions avoided – Sce. 1 (2)	34	41	35	29	30	29	31	35	44	37	*343*
CO_2 emissions avoided – Sce. 2 (2)	77	93	80	65	68	67	70	80	102	84	*785*
Total benefits – Sce.1 (3)=(1)+(2)	133	169	157	157	206	196	286	254	342	324	*2224*
Total benefits – Sce.2 (3)=(1)+(2)	177	221	203	194	244	233	325	299	399	371	*2666*
Public support (4)	152	336	151	112	150	147	147	234	297	206	*1931*
Net benefits – Sce.1 (5)=(3)-(4)	−19	−166	7	45	56	49	139	20	45	118	*293*
Net benefits – Sce.2 (5)=(3)-(4)	25	−114	52	82	94	86	178	65	102	165	*735*
Solar PV											
Energy import savings (1)	1	1	1	3	7	20	138	246	278	396	*1090*
CO_2 emissions avoided – Sce. 1 (2)	0	0	0	1	1	3	17	39	42	50	*154*
CO_2 emissions avoided – Sce. 2 (2)	1	1	1	1	3	8	38	89	95	115	*351*
Total benefits – Sce.1 (3)=(1)+(2)	1	1	2	3	8	23	155	285	320	446	*1244*
Total benefits – Sce.2 (3)=(1)+(2)	1	2	2	4	10	27	176	335	373	511	*1442*
Public support (4)	1	3	6	14	40	195	991	2634	2653	2401	*8937*
Net benefits – Sce.1 (5)=(3)-(4)	0	−2	−4	−11	−32	−172	−836	−2350	−2333	−1954	*−7693*
Net benefits – Sce.2 (5)=(3)-(4)	0	−1	−4	−10	−30	−167	−815	−2299	−2280	−1889	*−7496*
Solar CSP											
Energy import savings (1)	0	0	0	0	0	0	1	4	30	96	*131*
CO_2 emissions avoided – Sce. 1 (2)	0	0	0	0	0	0	0	1	4	12	*18*
CO_2 emissions avoided – Sce. 2 (2)	0	0	0	0	0	0	0	2	10	28	*40*
Total benefits – Sce.1 (3)=(1)+(2)	0	0	0	0	0	0	1	5	34	108	*149*
Total benefits – Sce.2 (3)=(1)+(2)	0	0	0	0	0	0	1	6	40	124	*171*
Public support (4)	–	–	–	–	–	–	14	28	185	427	*654*
Net benefits – Sce.1 (5)=(3)-(4)	–	–	–	–	–	–	−13	−23	−150	−319	*−505*
Net benefits – Sce.2 (5)=(3)-(4)	–	–	–	–	–	–	−13	−22	−145	−303	*−483*
Combined margin - Option B											
Wind energy											
Energy import savings (1)	214	255	362	629	844	937	1472	1268	1444	1633	*9057*
CO_2 emissions avoided – Sce. 1 (2)	55	63	85	121	126	148	163	184	197	201	*1343*
CO_2 emissions avoided – Sce. 2 (2)	126	144	194	276	288	339	374	421	450	458	*3070*
Total benefits – Sce.1 (3)=(1)+(2)	269	317	447	749	970	1086	1635	1452	1641	1834	*10,400*
Total benefits – Sce.2 (3)=(1)+(2)	340	398	556	904	1132	1276	1846	1689	1894	2092	*12,126*
Public support (4)	379	753	452	613	866	1004	1156	1619	1964	1710	*10,515*
Net benefits – Sce.1 (5)=(3)-(4)	−110	−436	−5	136	104	82	480	−167	−323	124	*−116*
Net benefits – Sce.2 (5)=(3)-(4)	−39	−355	104	291	266	273	690	70	−70	382	*1611*
Small hydro											
Energy import savings (1)	94	113	108	114	151	141	212	178	224	206	*1541*
CO_2 emissions avoided – Sce. 1 (2)	24	28	25	22	23	22	24	26	31	25	*249*
CO_2 emissions avoided – Sce. 2 (2)	55	64	58	50	52	51	54	59	70	58	*570*

Total benefits – Sce.1 (3)=(1)+(2)	118	142	133	136	174	163	236	204	255	231	*1790*
Total benefits – Sce.2 (3)=(1)+(2)	149	178	165	164	203	192	266	237	294	263	*2111*
Public support (4)	152	336	151	112	150	147	147	234	297	206	*1931*
Net benefits – Sce.1 (5)=(3)-(4)	−34	−194	−18	24	24	16	89	−30	−42	24	*−141*
Net benefits – Sce.2 (5)=(3)-(4)	−3	−158	14	52	53	45	119	3	−3	57	*180*
Solar PV											
Energy import savings (1)	1	1	1	2	6	17	115	200	210	283	*835*
CO_2 emissions avoided – Sce. 1 (2)	0	0	0	0	1	3	13	29	29	35	*110*
CO_2 emissions avoided – Sce. 2 (2)	0	0	1	1	2	6	29	66	65	79	*251*
Total benefits – Sce.1 (3)=(1)+(2)	1	1	2	3	7	19	128	229	238	318	*945*
Total benefits – Sce.2 (3)=(1)+(2)	1	1	2	3	8	23	144	266	275	362	*1086*
Public support (4)	1	3	6	14	40	195	991	2634	2653	2401	*8937*
Net benefits – Sce.1 (5)=(3)-(4)	0	-2	-5	-11	-33	-176	-863	-2406	-2415	-2083	*-7993*
Net benefits – Sce.2 (5)=(3)-(4)	0	-2	-4	-11	-32	-172	-847	-2368	-2378	-2038	*-7851*
Solar CSP											
Energy import savings (1)	0	0	0	0	0	0	1	3	23	68	*96*
CO_2 emissions avoided – Sce. 1 (2)	0	0	0	0	0	0	0	1	3	8	*12*
CO_2 emissions avoided – Sce. 2 (2)	0	0	0	0	0	0	0	1	7	19	*28*
Total benefits – Sce.1 (3)=(1)+(2)	0	0	0	0	0	0	1	4	26	77	*108*
Total benefits – Sce.2 (3)=(1)+(2)	0	0	0	0	0	0	1	5	30	88	*123*
Public support (4)	–	–	–	–	–	–	14	28	185	427	*654*
Net benefits – Sce.1 (5)=(3)-(4)	–	–	–	–	–	–	−13	−24	−159	−350	*−546*
Net benefits – Sce.2 (5)=(3)-(4)	–	–	–	–	–	–	−13	−23	−155	−339	*−531*

Sce. 1: Scenario 1. CO_2 price: €14/tCO_2 – Mode [55].
Sce. 2: Scenario 2. CO_2 price: €32/tCO_2 – Median [55].

not taken into account the life-cycle emissions. The life cycle of components manufacturing, installation, operation, maintenance and transportation of renewable energy plants means that non-renewable energy is used and, thus, that greenhouse gases are emitted, as some authors have analysed [58–61]. These studies point in the same direction: the life cycle emissions from renewable energy plants are orders of magnitude lower than those from fossil-fuel fired plants. This paper does not consider the life cycle of components regarding energy use nor emissions, whether renewable or non-renewable. Those studies suggest that, if we had taken the life-cycle emissions from electricity generation plants into account, the emissions reductions from RES-E deployment would have been even greater. However, since to our knowledge no study on those life cycle emissions is available for Spain, we have not included them in our calculations. Further research should continue the efforts of those authors in identifying the life-cycle CO_2 emissions of power plants whether in Spain or elsewhere.

Secondly, it is usually claimed that, apart from reductions of CO_2 emissions and fossil fuel impacts, RES-E deployment leads to net employment creation, rural and regional development opportunities, industry creation and innovation. Finally, other costs of RES-E support, including back-up costs and distribution and transmission costs, have not been included in the calculation. RES-E deployment has also led to a lower than expected use of recently installed CCGTs (see Ref. [62] for further details). Those aspects should be considered in further research.

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